REQUISITE CONDITIONS FOR THE FORMATION OF ICE RAMPARTS

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In a recent paper[1] Mr. J. B. Tyrrell, late of the Geological Survey of Canada, has made the assertion that though he has now for many winters made observations on and about the Canadian Lakes, he has never detected any evidence of ice push against shores as a result of expansion. He thus discredits the accepted explanation of ice ramparts. To one who has in other localities seen the ramparts *in process of formation* from this cause, it seems important to supply an explanation for the failure of such an experienced and careful observer as Mr. Tyrrell to observe the same phenomenon.

The quite obvious fact is that ice ramparts are greatly restricted in their occurrence, a number of special conditions being essential to their formation. Mr. Tyrrell's paper fortunately shows that some of these conditions were lacking in the districts which he studied.

In order that these requisite conditions may clearly be understood, it will be necessary to give in brief outline the theory of formation of normal ice ramparts through ice expansion. The initial ice cover of the winter season on our northern lakes usually forms with only moderately cold air temperatures. These may be assumed to be but a few degrees below the freezing point, and the cover, once formed to a thickness of an inch, grows quite slowly from the under surface. After it has acquired a considerable thickness, the arrival of one of the "cold waves" contracts the ice cover by lowering its temperature through contact with the colder air layers. Under this contraction fissures open in the ice to the accompaniment of loud rumblings, water rises to fill them and is

[1] J. B. Tyrrell, "Ice on Canadian Lakes," *Trans. Can. Inst.* (1910), IX, 1–9 (reprint), pls. 1–6.

quickly frozen in the prevailing low temperature so as to form intercalated "planks" of younger ice. The lake cover is thus again completed at a low temperature, so that a "warm wave," *if it can quickly communicate its temperature to the ice*, causes an expansion which according to Tyrrell amounts to one to three inches per mile per degree Fahrenheit. Thus expanded the ice cover is too large, and a push is exerted against the shore *if the cover is a structure competent to transmit the stresses induced in it.* The range of action of this push, and the consequent *size of the ridge raised upon the shore will depend upon the number of times the process is repeated;* for each alternation of "cold" and "warm" wave introduces a new series of wedges into the ice cover and correspondingly extends its margins.

To recapitulate: (1) there must be a wide and probably also a relatively sudden alternation of lower and higher air temperatures over the lake: (2) these temperature changes must be promptly communicated to the ice; (3) the ice cover regarded as a girder must be competent to transmit the stresses to the shore; and (4) for large effects the alternations of temperature must be several times repeated. Obviously, also, the shores of the lake must be of such form and materials as to be subject to movement under stresses below the crushing strength of the ice itself.

The first and last conditions are meteorological and can be determined for any given district. Not only is a severe winter climate essential, but there must be an alternating occurrence of cold and warm waves.

The second and third conditions are crucial. In Buckley's studies of ice ramparts at Madison, Wisconsin, the most thorough that have been made,[1] it was found that ramparts seldom formed during seasons when the lakes were snow covered. The probable explanation of this is that snow blankets the ice and prevents a *quick* communication to it of the air temperatures above the snow surface. We have here emphasized the element of time, for the reason that studies in Greenland show that air temperatures are *slowly* communicated downward through snow blankets to very

[1] E. R. Buckley, "Ice Ramparts," *Trans. Wis. Acad.* (1901), XIII, 141–62; pls. 1–18 (discussion by C. R. Van Hise).

considerable depths. It is well known from studies of the "fatigue" of materials under stress that they often yield to slowly acting stresses that would be transmitted undiminished in intensity if quickly applied. Snow blanketing of the ice, from the evidence in Mr. Tyrrell's paper, would appear to be very general within the districts which he studied.

Further limitations upon the formation of ice ramparts are imposed by the third condition—the incompetency of the ice cover as a transmitter of stresses. With the ice serving as a strut,

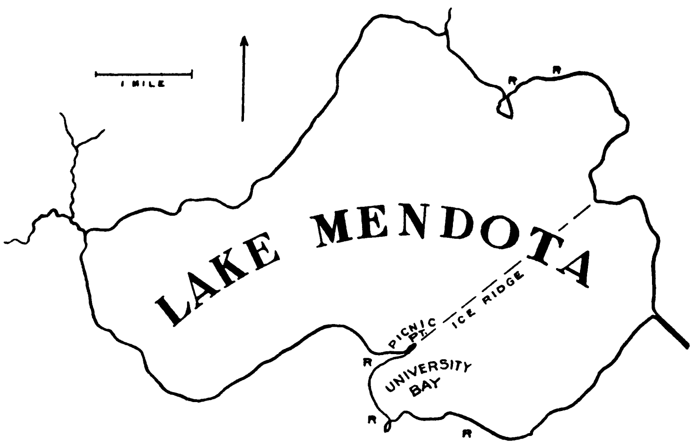

FIG. 1.—Sketch map showing the position of ice ramparts and of buckled ice ridge formed on Lake Mendota at Madison, Wisconsin (based on Buckley's Map).

its push can be transmitted effectively *only when the cover is maintained as a plane surface.* Lack of homogeneity or of absolute uniformity in strength, and variation in form of the surface at which stress is applied, will with increasing length of beam introduce an important stress component tending to buckle the beam and dissipate the energy transmitted by it—the competency of a strut to transmit stresses is inversely as its length. Experience shows that lakes or arms of lakes which are much over a mile and a half across do not develop important ice ramparts. On Lake Mendota at Madison, the best ramparts are found upon the shores of University Bay, which is about three-fourths of a mile across. Outside this bay the lake ice is raised each winter into a sharp

ridge extending from the outer margin of the bay (the peninsula of Picnic Point) across the wide portion of the lake to the opposite shore, and about this section no ramparts are developed (see Fig. 1).

Ice ramparts can thus form only on shores of lakes which have relatively small size or on small bays of larger lakes, though a width of at least half a mile is probably necessary in order to secure sufficient dilatation of the ice cover to make ramparts of appreciable size.

Anything which tends to deform the ice cover from a perfect plane will effectively destroy its competency as a girder, and then no ramparts will form. Mr. Tyrrell has shown in his valuable paper that young lake ice will support, without bending, less than its own thickness of dry snow, and that the ice on Canadian lakes is bowed down under its load of snow to such an extent that water comes to the surface through cracks and further increases the bending.

To sum up, the heavy snow cover alone would by blanketing the ice, but probably even more by bending it, effectually prevent the formation of normal ice ramparts. As already stated, such ramparts may actually be seen in process of formation during a warm wave in any favorable winter about Lake Mendota at Madison, Wisconsin.

It is fully realized that rafts of floating ice drifted by the winds at the time of the spring "break up" do also produce small bowlder ridges on shores which bear a close resemblance to some of the types of normal ice ramparts.